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CRANFIELD INSTITUTE OF TECHNOLOGY

AEROPLANE DESIGN STUDY

STOL AIRLINER (A71)

PART 3 LOW SPEED LIFT AND CONTROL

by

R .E .WARD

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Restricted



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College of Aeronautics

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SUMMARY

The potential application of advanced forms of aircraft control to civil operation appears to be capable of being split into two areas. First, those aircraft which are very large, whose rotary inertia tends to reduce the effectiveness of conventional controls. Second, those aircraft whose specification dictates that the aeroplane be flown at very low speed. Again conventional controls become inefficient due to decreased aerodynamic efficiency.

The second category of aircraft has been considered in the form of an STOL aircraft. The control problems of an STOL aircraft with a 2000 ft runway capability (Ref.10) have been examined. It has been found that the aircraft is unstable and could require autostabilisation. None of the conventional controls were satisfactory and each required augmentation. The single strip crosswind requirement penalises the design most heavily since this requires over half of the extra control power necessary. The total augmentation for blowing air amounts to an equivalent thrust of approximately 6700 lb. This is equivalent to 11.5 per cent of the total installed aircraft thrust.

CONTENTS

	<u>Page</u>
NOTATION	
1. INTRODUCTION	1
2. TAKE OFF	2
3. LONGITUDINAL CHARACTERISTICS	3
3.1 Longitudinal trim on approach	3
3.2 Tail authority to trim	3
3.3 Longitudinal trim after engine failure	3
3.4 Excursions from the trimmed condition	3
4. LATERAL CHARACTERISTICS	4
4.1 Single strip cross wind operation	5
4.2 Control after engine failure	6
5. DISCUSSION	7
5.1 Take off	7
5.2 Landing	8
5.3 Total blow requirements	8
6. CONCLUSIONS	8
REFERENCES	10

Table

Summary of lateral aerodynamic derivatives during a trimmed approach.

Figures

1. Comparison of two possible take off procedures
2. Variation of take off distance with all up weight
3. Aircraft acceleration capacity at take off
4. Engine out acceleration capacity at take off
5. Trimmed incidence versus speed for A71
6. Trimmed lift coefficient versus speed for A71
7. Variation of power setting with C_{μ} and speed for A71
8. Down tail load from trim on approach
9. Elevator required for trim on the landing approach
10. Engine power to maintain lift after engine failure
11. Acceleration capacity along glide slope at 79 knots
12. Variation of acceleration from balance point when aircraft flying down glide path at 79 knots - constant power
13. Variation of acceleration from balance point when aircraft flying down glide path at 79 knots - constant incidence
14. Elevator required to trim increasing power at 79 knots
15. Aircraft response to step elevator at 79 knots, $C_{\mu a} = 1.0$
16. Lateral stability characteristics, stick fixed, on approach
17. Characteristics of spiral mode with n_v and l_v at 80 knots
18. Characteristics of Dutch roll damping with n_v and l_v at 80 knots
19. Characteristics of Dutch roll time period with n_v and l_v at 80 knots
20. Characteristics of rolling mode with n_v and l_v at 80 knots
21. Wind distribution at Speke
22. An approximate relationship between mean wind speed and gust velocity
23. Percentage available of control power required to maintain a steady sideslipping approach
24. Rudder momentum coefficient required to trim crosswind landing
25. A.P.U. thrust required for rudder blow
26. Rolling and yawing moment coefficients due to port outboard engine failure on approach
27. Percentage available of control power required to trim port outboard engine out with zero sideslip
28. Aileron momentum coefficient required to provide sufficient blow for roll control with engine out
29. A.P.U. thrust required for aileron blow

1. INTRODUCTION

The potential use of advanced forms of aircraft control for civil operations appears to be able to be split into two areas. First, those aircraft which are very large, whose rotary inertia tends to reduce the effectiveness of conventional controls (Ref.12). Second, those aircraft whose specification dictates that the aeroplane be flown at very low speed. Again conventional controls become inefficient due to decreased aerodynamic efficiency.

There is some suggestion that a medium size short range STOL aircraft, which comes into the second category, might be economically feasible. This is due to its potentially shorter turn round time and extra flexibility compared with conventional short range aircraft. It is possible to make certain qualitative observations about control problem areas for this category of aircraft (Ref.3). However a quantitative feasibility study requires the investigation of a particular aircraft type.

For this reason a specification for an STOL aircraft has been developed (Ref.10) in order that the low speed control aspects can be investigated. The aircraft uses externally blown jet flaps to allow an approach speed of 79 knots whilst still retaining a relatively high wing loading of 74 lb/ft^2 . This allows a high cruising speed to be achieved. The low speed aerodynamic characteristics of the aircraft (Ref.10) have largely been derived from recent wind tunnel tests carried out at NASA on similar types of aircraft. The main problem areas on this aircraft have proved to be the single strip crosswind operation and the control after an outboard engine failure. These are the aspects of control which have been considered in most detail.

The basic specification and configuration of the aircraft are described in Part 1 of the report (Ref.10), whilst Part 2 will be concerned with a description of certain detail design features.

2. TAKE OFF

The take off procedure is described in part 1 of the report (Ref.10), that is, the aircraft accelerates with flaps at the take off setting to the safety speed before the thrust deflector is moved up. Figure 1 illustrates this take off distance required compared with deploying the flaps and the deflector at the take off safety speed. As can be seen, the difference in distance is relatively small. However, it is felt that the original procedure provides a neater solution since it reduces pilot workload at unstick.

Figure 2 shows the variation of take off distance with all up weight. At the estimated gross weight of 115,000 lb the 2000 ft take off cannot quite be achieved, indicating that the nominal thrust/weight ratio of 0.5 is barely sufficient. This lack of power is again shown in figure 3 which shows the relatively modest accelerations attainable at unstick, which severely limits the climb out performance.

The engine out performance poses a most difficult problem because of the interaction between thrust and lift. B.C.A.R. requirements state that the speed at the decision point should be at least equal to the minimum control speed with one power unit not operating. If it is assumed that for a given momentum coefficient and incidence the axial force is unaltered by engine failure, the acceleration diagram, engine out, is as shown in figure 4. Even neglecting the control problem, we note that the balance point of thrust equals drag and lift equals weight is greater than 190 ft/sec. This requirement then overrides the $1.2V_{S1}$ at screen height and results in a gross take off distance of about 2600 ft. This is clearly unacceptable for civil operation. It would require an increase in thrust/weight ratio although cross coupled fans might go some way to solving the problem.

3. LONGITUDINAL CHARACTERISTICS

This report is mainly concerned with the problems of lateral control. There is however a need to demonstrate that the longitudinal capability of the aircraft is adequate and that the approach speed is not so low that the powered lift requirement is excessive. The total blowing air requirement also needs to be estimated and preliminary calculations indicated that tailplane blowing would probably be necessary.

3.1 Longitudinal trim on approach

The aircraft approaches down a $7\frac{1}{2}^\circ$ glide slope with trailing edge flap set at 20° plus 20° on the aft segment. With the thrust deflector up, this produces large nose down pitching moment coefficients (> 1 at normal approach speed) which are strongly affected by the c.g. position. Lift and thrust are both markedly dependent on power setting and incidence. It is important therefore to establish a trimmed condition since this determines the stability characteristics of the aeroplane which are also dependent on power and incidence (Ref.10). The use of the usual iterative technique produces the results shown in figures 5, 6 and 7.

It is encouraging that at the suggested approach speed of 79 knots, the aircraft attitude is almost horizontal (approx. 1° nose up). This removes the problem of a possible nose wheel landing as experienced by the Breguet 941 while under trials with American airlines (Ref.1). It will be noted that the power requirements are relatively large, the thrust in the suggested approach condition being nearly 60 per cent of maximum. It may be that some of the advantages of the $7\frac{1}{2}^\circ$ glide slope in reducing noise 'footprint' area could be lost due to this high power requirement.

3.2 Tail authority to trim

Tail loads required for trim are shown in figure 8. Assuming linear lift curve slopes, the elevator angle to trim is as shown in figure 9. In the low speed approach the tail efficiency is approximately 1.3. As an example, if a 79 Kt approach is considered with a tail setting of 0° then approximately 19° of elevator is required for the forward c.g. position, this is associated with an effective tail incidence of 5° . On this basis trim is possible but little remains for control. This suggests the need for some sort of augmentation, tailplane blow offering an attractive solution. The amount of blowing required is obviously dependent on control requirements and hence is discussed in section 3.4.

3.3 Longitudinal trim after engine failure

It is assumed that the trimmed power requirement, engine out, may be deduced from the all engines operating condition on the basis of equal C_L . Using this assumption it is found that the trimmed incidence does not change markedly for a given speed. It has thus been assumed that the trimmed incidence is as for all engines operating. There is also evidence to suggest that aerodynamic and control derivatives are unaffected by having one engine inoperative for a given total engine thrust (Ref.2). Using these assumptions the engine power required to trim an engine failure is as shown in figure 10. It can be seen that at the higher speeds the increase in total engine thrust is modest but at the low speed condition where the powered lift proportion is greater, the total thrust required is increased by approximately 25 per cent. On the same diagram is plotted the aircraft thrust characteristics from which it is clear that trim is impossible below 70 Kts. The control problem after an engine failure may be considered as a separate issue and is discussed in section 4.2.

3.4 Excursions from the trimmed condition

The manoeuvring capability of the aircraft at the suggested approach speed of 79 Kts is illustrated in figure 11. The upper boundary of the figure corresponds to maximum take off power which is limited to 5 minutes per flight. The accelerations are untrimmed values corresponding to an instantaneous change in incidence or power.

Two possible methods of controlling aircraft position relative to the glide path are shown in figures 12 and 13. If it is assumed that normal acceleration is the means by which control is effected, it can be seen that constant power results in a small trim change associated with a large deceleration and vice versa for constant incidence. It seems that on the approach path, power would be used to control the aircraft height as is the case with more conventional aircraft

If the constant incidence case is considered first with the tail setting fixed at 0° , then the application of blowing air over the elevator results in the elevator angles to trim out of balance pitching moments due to increasing power shown in figure 14. The results have been obtained using reference 4. This reference suggests that there is evidence to support linearity of lift curve slope with control angle up to deflections of approximately 50° for $C_u \geq 1$. If a momentum coefficient of unity is used, this reduces the elevator angle for trim to approximately 10° and allows a greater range of elevator for manoeuvre.

The flare manoeuvre can only be achieved by use of an elevator, the design normal acceleration during the flare is $0.25g$ although it is desirable that more than this should be available. The response to step application of elevator is shown in figure 15. Approximately 10° of elevator is required to produce $0.25g$. The time response is rather slow and in practice the pilot would probably use a larger deflection until the flare started to develop. If 20° is allowed for manoeuvre then the total movement including trim is acceptably small. A momentum coefficient of unity based on tailplane area means a bleed air requirement of approximately 1200 lb equivalent thrust including losses.

The aircraft has a very large tailplane (\bar{V} approximately 1) but blowing has still proved to be necessary. Therefore it seems that for these very slow approaches the tailplane size should be determined for a conventional landing, for example an abort after A.P.U. failure. The amount of blowing should then be determined to give sufficient tail authority for the low speed case.

Since this report is mainly concerned with lateral control problems, the symmetric gust case has not been considered. However, it is probably safe to assume that since a large proportion of powered lift is being used, the incidence margins available in absolute terms will be at least of the same order as for conventional aircraft. The assumption has thus been made that response to symmetric vertical gusts will not constitute a design problem. The relatively low power of the aircraft could provide problems for the longitudinal gust case but this is not essentially a control issue and hence has been neglected.

4. LATERAL CHARACTERISTICS

The stick fixed lateral stability characteristics of the aircraft are shown in figures 16 to 20. The aerodynamic derivatives from which these results were obtained are summarised in table 1. It can be seen that the spiral instability is very strong with a time to double amplitude of only 14 sec at the approach speed of 79 Kts. The Dutch roll is also unstable with a rather long time period but since the damping is so small this might be acceptable. This instability has been predicted in theory (Ref.3) and found in practice (Ref.5) and is due to the changed ratio between

inertial and aerodynamic forces compared with higher speeds. It can be seen from the figures that even large variation of the two easily controllable derivatives n_v (fin area) and l_v (dihedral) causes little improvement in the characteristics. On this basis it seems that the aircraft would feel very sluggish to the pilot at these speeds and some form of autostabilisation would be very desirable.

4.1 Single strip cross wind operation

The aircraft is designed to operate off a single strip which means landings must be made with large sideslip angles. Preliminary investigations (Ref.6) showed that these angles should correspond to a crosswind of approximately 28 Kts. At the speeds considered this requirement is very severe. There are also gust cases to be considered. The determination of these gust cases requires a statistical evaluation of a large number of sites and is not practicable in the context of this report. However it is possible to evaluate gust velocities approximately by considering a single site. As for reference 6 Speke has been chosen as this site since it is in an exposed coastal area where the mean wind speed over the year tends to be high. Figure 21 shows the distribution of mean wind speed in all directions; Reference 7 indicates that gust velocity is related to this mean wind speed as might be expected. Figure 22 shows the relationship between mean hourly wind speed and gust velocity over a 5 second period. With flaps in the landing position there will be two cases which certainly need to be considered;

- a) Aircraft not aligned with runway direction, zero cross wind with maximum side gust.
- b) Aircraft aligned with runway direction, 28 Kt cross wind with reduced side gust.

As can be seen from figure 22 the gust associated with maximum wind speed is 19 Kts. If advantage is taken of a most favourable orientation of the runway, the gust velocity becomes 13 Kts.

The unblown performance of the fin and rudder can be considered to illustrate the control problem areas. The primary requirement must be that the aircraft should be able to approach on a steady sideslip corresponding to a cross wind of 28 Kts, the alternative 'crabbed' approach is not considered since the control power required in this case is less in the steady state. If the rudder angle is limited to 15° to cater for lateral gusts and manoeuvre then the percentage available of the control power required for a sideslipping approach is shown in figure 23. It will be noted that at the suggested approach speed the control power available is rather less than 50 per cent of what is required.

Even with a dorsal fin it is clear that fin stall is a possibility at these large sideslip angles. There is evidence (Ref.11) that a dorsal will only delay the stall over the area of fin which it covers and hence marked non linearities in control power can be expected. Blowing over the rudder will delay separation although it is difficult to predict how much blow is required without tests on the particular configuration. Since such large amounts of extra control power are required it will be assumed that the blowing air required for control is sufficient to prevent fin stall.

As in the case of the blown tailplane it is possible to use large control angles when the momentum coefficient is greater than unity. The availability of these large control angles is essential since the blowing over the rudder has a slightly greater effect on the weathercock stability than on the control effectiveness. Hence for equal control angles rudder blowing would be detrimental to crosswind landing performance. If allowance is made for the stalling of the control at low values of C_{μ} , figures 24 and 25 are obtained. These show the amount of air required to be equivalent to a thrust of 3500 lb on the approach if a control angle limit of 40° is applied.

An alternative to rudder blowing was considered in the use of a blown pole at the forward end of the fuselage for providing lateral control power. This has the advantage that it is possible to increase control power without increasing weathercock stability at the same time. However the A.P.U. thrust requirement was of the order of 1000 lb and the pole area 13 ft^2 . It was thought that the additional ducting weight and complication of this arrangement, which presumably would have had to be retractable, was difficult to justify since some fin blowing would be necessary to prevent stalling in any case.

Initial calculations on the unblown aircraft showed that the lateral gust reponse was satisfactory but with a time period of approximately 8 secs. Since the rudder blow has a large effect on the weathercock stability it may be deduced that the blown performance is also likely to be acceptable although some simulator work is desirable here to test pilot opinion.

4.2 Control after engine failure

B.C.A.R. requirements require that with any one engine out the rudder control power must be sufficient to correct swing and maintain heading. The power of the rudder is not the critical factor for an externally blown flap aircraft. As a large proportion of the thrust is used to produce lift then the loss of an engine produces large rolling moments. The ratio of the out of balance rolling to yawing moment due to an engine failure at trimmed approach conditions is illustrated in figure 26.

If it is assumed that the aircraft is flown with zero sideslip and that the aileron angle to trim engine failure is limited to 15° , then the percentage available of control power required is shown in figure 27. Again the need for some form of augmentation is revealed.

One answer to this problem when the failure is in the gas generator is to couple the fans of each pair of engines. This would require that the second engine on the failed side be set at maximum take-off, the remaining small out of balance rolling moment being held by conventional aileron power. A preliminary study (Ref.9) indicated that although this type of cross coupling is feasible, the total installed weight of the system would be in excess of 1000 lb. This is rather a large penalty to cater for a case which may occur only very rarely. It also does nothing to cater for the fan disc failure case which must be a possibility in view of the extra complication of the variable pitch blading.

Another possibility for control is to move the aft segment of the flap differentially but this would involve a significant roll/yaw coupling. It is felt that this solution would be mechanically complicated and there is no certainty that the result would be acceptable.

A third solution and the one which has been adopted is to use blowing air over the knee of the aileron. Since the adverse yawing moment associated with blowing is relatively small the roll/yaw coupling is less than for differential flap control. If the assumption is made that the aileron stalls at 20° deflection in the unblown condition, and thereafter produces no more lift, and that when $C_u = 1$ the aileron stall is prevented up to 50° then the results shown on figures 28 and 29 are obtained. The former shows the momentum coefficient required and the latter the equivalent bleed air thrust. If a limit of 40° is placed on aileron deflection it can be seen that a thrust of approximately 2000 lb is required at the approach speed of 79 Kts.

5. DISCUSSION

5.1 Take off

In general the take off produces less of a control problem than landing because the minimum airspeed is 20 Kts greater. However the feasibility of this type of aircraft does appear to hinge on an acceptable take off and climb procedure being established. The difference in the safety speed with the thrust deflector up and down, with the flaps at the take off setting, is almost 30 Kts. The steady climb angle available is only about 5° and the accelerations available are small so the noise footprint area could be increased markedly. The transition to aerodynamic from powered lift would be improved by selection of landing flap setting with deflector down, but this would merely reduce the speed increase required with deflector up and the problem of getting a steep climb out angle still remains. It does appear that the solution to this and the engine fail problem is a substantial increase in thrust-weight ratio, to approximately 0.6, which is costly in installed weight and also possibly in fuel. The turning efficiency of the deflector plate is relatively low and it might be that improved aerodynamic design could give a higher effective thrust.

5.2 Landing

The engine out condition on landing is less damaging to the operational feasibility of the aircraft than the cross wind landing. The advantage of the relatively widely spaced engines is that more efficient spreading of the engine exhaust gasses is achieved thereby improving the lifting capacity. It may be that a reduction in low speed lift capacity could be tolerated and the outboard engines moved in. This would not only have the advantage of reducing the rolling moment arising from an engine failure but would make cross coupled fans more attractive due to the reduced weight penalty.

The tentative gust cases suggested in section 4.1 add to the severity of the single strip all weather requirement. However once rudder blowing has been accepted the additional penalty on blowing air due to the gust is small. The operator is being asked to pay a heavy price for this type of cross wind operation and it is questionable whether it is economically feasible to do so.

5.3 Total blow requirements

Circulation control of the tailplane, rudder and aileron have been shown to be necessary as well as the probable need for autostabilisation. The extra system complication and weight of these measures will penalise the design very severely compared with a more conventional short range aircraft. The major power requirement is for rudder blowing due to the cross wind, single strip, approach. The need to ensure that fin stall is avoided requires rudder blow although this is an inefficient way of producing the required control power. The total blowing requirement amounts to an APU mass flow equivalent to a thrust of approximately 6700 lb. The APU chosen for the A71 for air conditioning and pressurisation is the AiResearch GTCP85-98 which has a rated capacity of 110 lb/min and is clearly unacceptable. It seems that the aircraft could be re-engined with RB419 engines rather than RB410. These engines produce approximately 19000 lb of thrust compared with 14500. This would provide a thrust-weight ratio of about 0.67. This is rather higher than desirable but if the bleed air thrust is held in reserve then the effective thrust-weight ratio would drop to 0.6 and solve the engine out problem at take off. The weight of the ducting to the blown surfaces is about 400 lb; the change of engines would produce a further weight increase of 5300 lb. Although these weights are not the total penalty for STOL operation they are directly attributable to short field performance.

6. CONCLUSIONS

1) The aircraft as considered has insufficient power to comply with engine out requirements on take off as specified for civil operation.

2) The relatively high power approach could be seriously detrimental to noise footprint area.

3) Circulation control is necessary on elevator, rudder and aileron for this type of configuration.

4) The requirement of single strip operation penalises the design most heavily and should be re-examined in the light of operator requirements.

5) The aircraft is unstable laterally and would almost certainly require autostabilisation of some sort.

6) The requirement for blowing air over the controls cannot be produced by APUs of the sizes currently available. It seems that engines which are designed for large amounts of bleed air offtake will be necessary on STOL airliners. The RB419 engine is suitable for this purpose and since it has a high rated thrust the take off performance would then be acceptable.

7) The 2000 ft runway length requirement introduces penalties which appear to be unacceptably severe. If the noise footprint area needs to be minimised rather than the runway length, then there are alternative means of doing this without penalising the design to the extent implied by the very low approach speeds associated with 2000 ft runway operation.

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TABLE 1

Summary of Lateral Aerodynamic Derivatives During a Trimmed Approach

Speed (Kts) Derivative	60	70	80	90	100
y_v	-0.426	-0.373	-0.330	-0.298	-0.278
y_p	-0.040	0.092	0.110	0.088	0.064
y_r	0.0036	0.0088	0.0136	0.0183	0.0230
l_v	-0.243	-0.236	-0.226	-0.212	-0.197
l_p	-0.620	-0.578	-0.518	-0.481	-0.465
l_r	0.423	0.397	0.371	0.348	0.322
n_v	0.329	0.301	0.268	0.240	0.221
n_p	-0.247	-0.219	-0.195	-0.177	-0.164
n_r	-0.188	-0.188	-0.188	-0.188	-0.188

COMPARISON OF TWO POSSIBLE TAKE OFF PROCEDURES

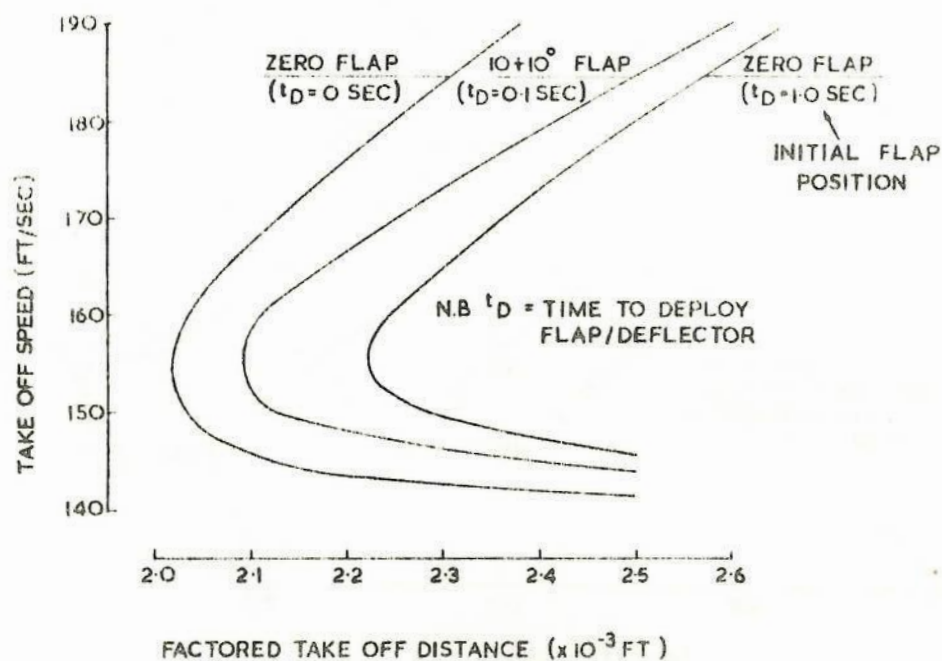


FIG 1.

VARIATION OF TAKE OFF DISTANCE WITH A.U.W.

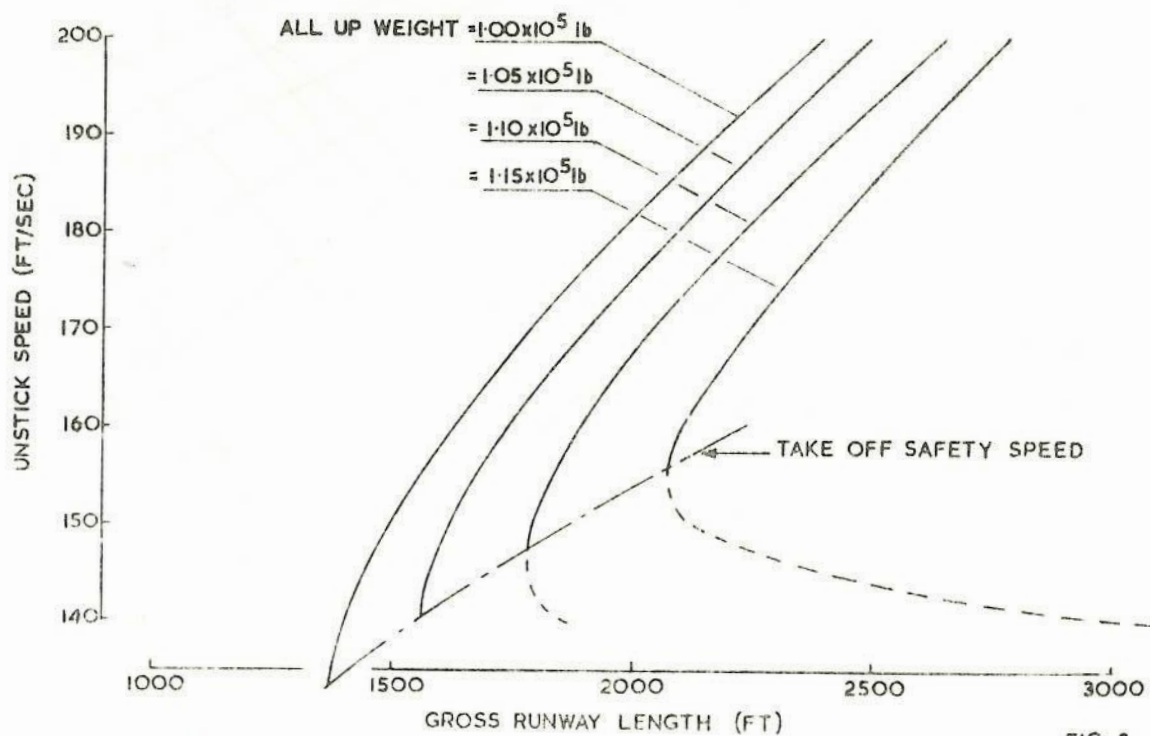
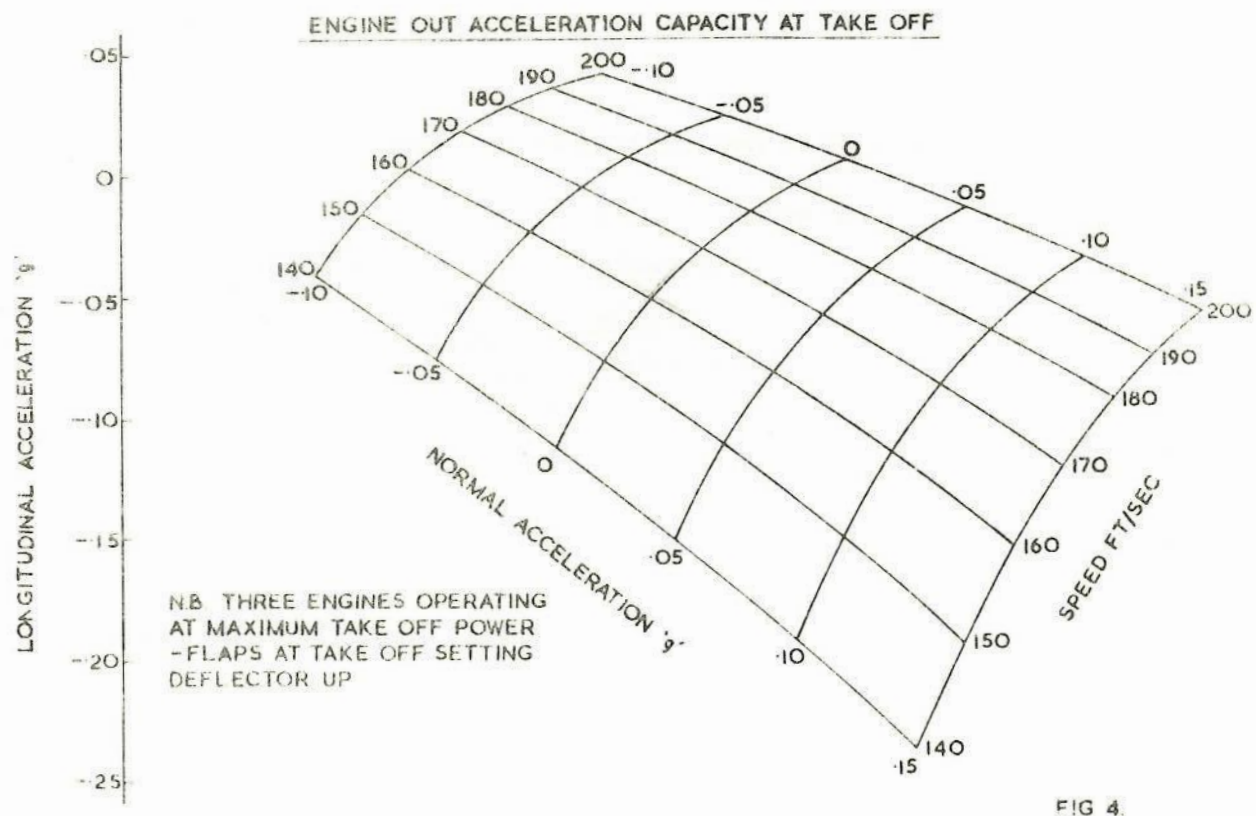
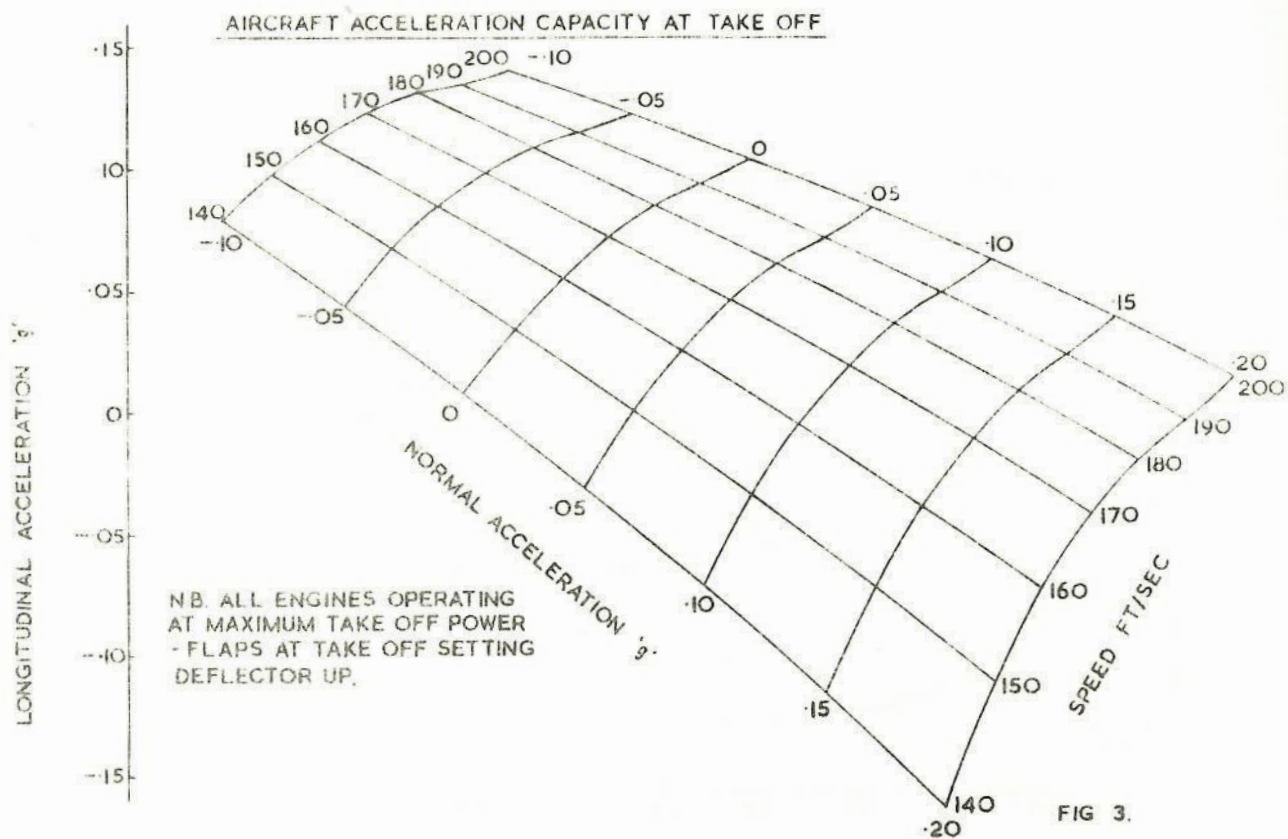


FIG 2.



TRIMMED INCIDENCE VERSUS SPEED FOR A71

LANDING CONDITION ($7\frac{1}{2}^\circ$ GLIDE ANGLE 20+20 FLAP)

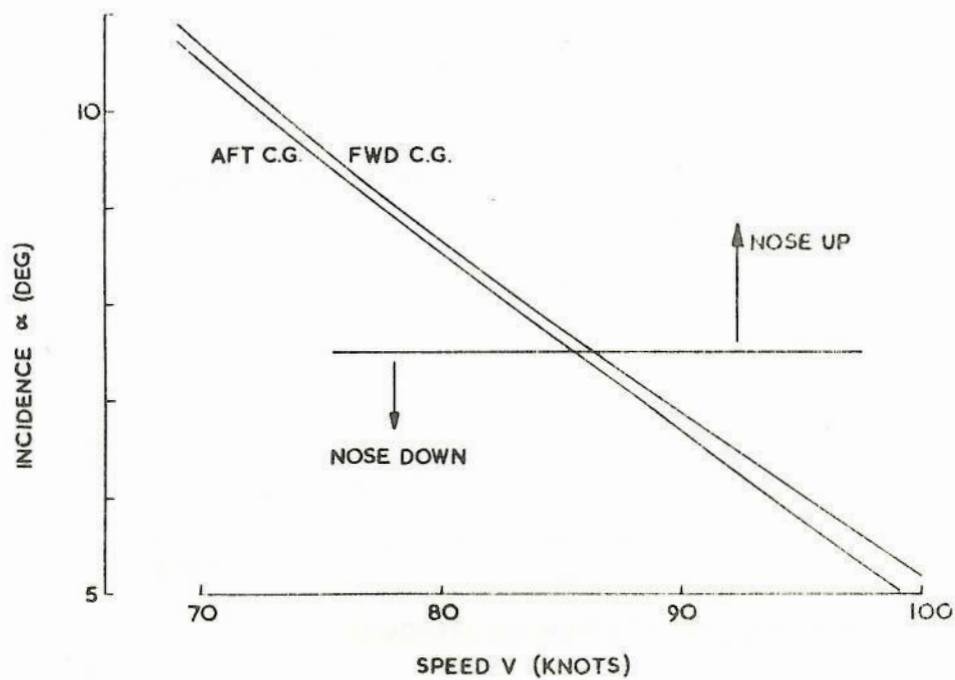


FIG 5.

TRIMMED LIFT COEFFICIENT VERSUS SPEED FOR A71

LANDING CONDITION ($7\frac{1}{2}^\circ$ GLIDE SLOPE 20+20 FLAP)

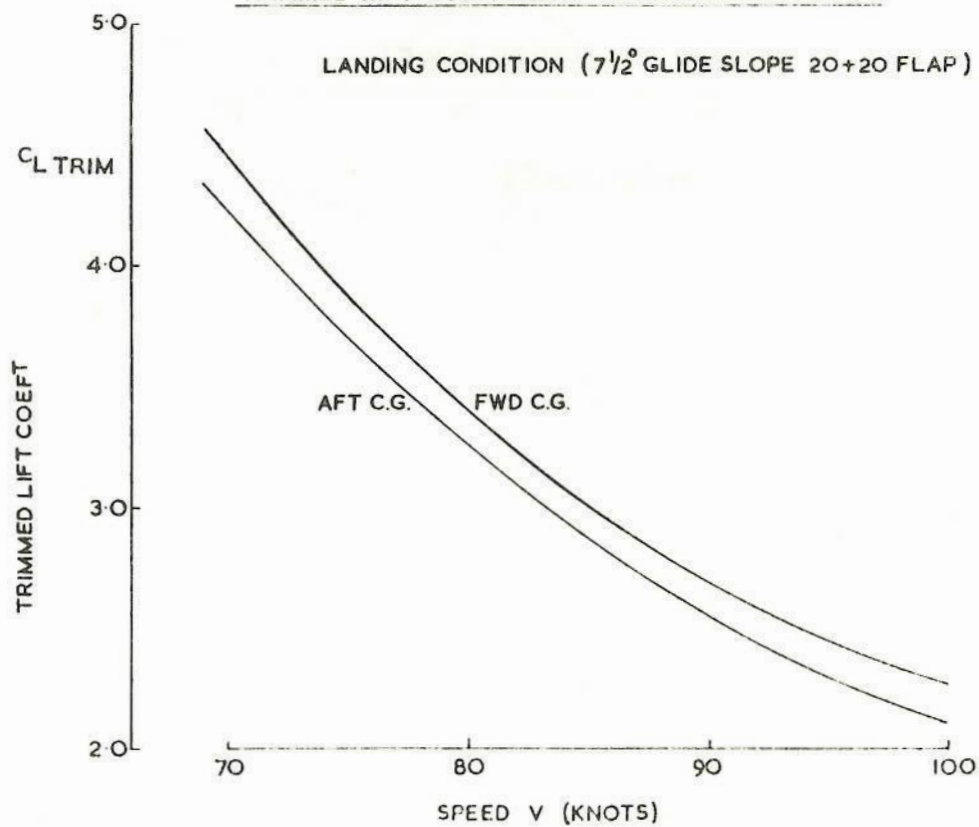
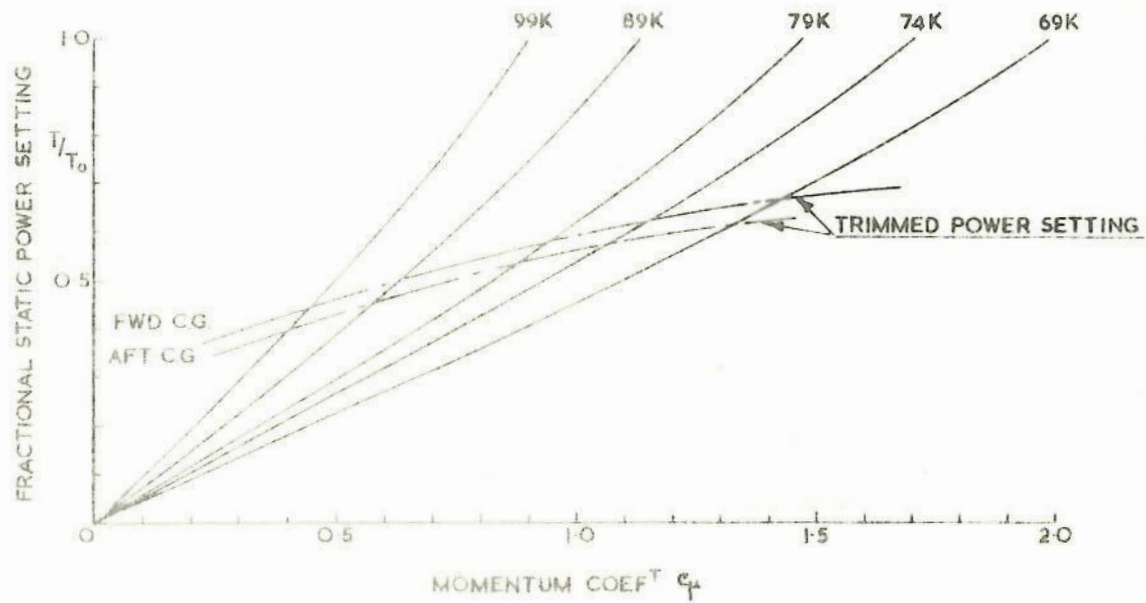


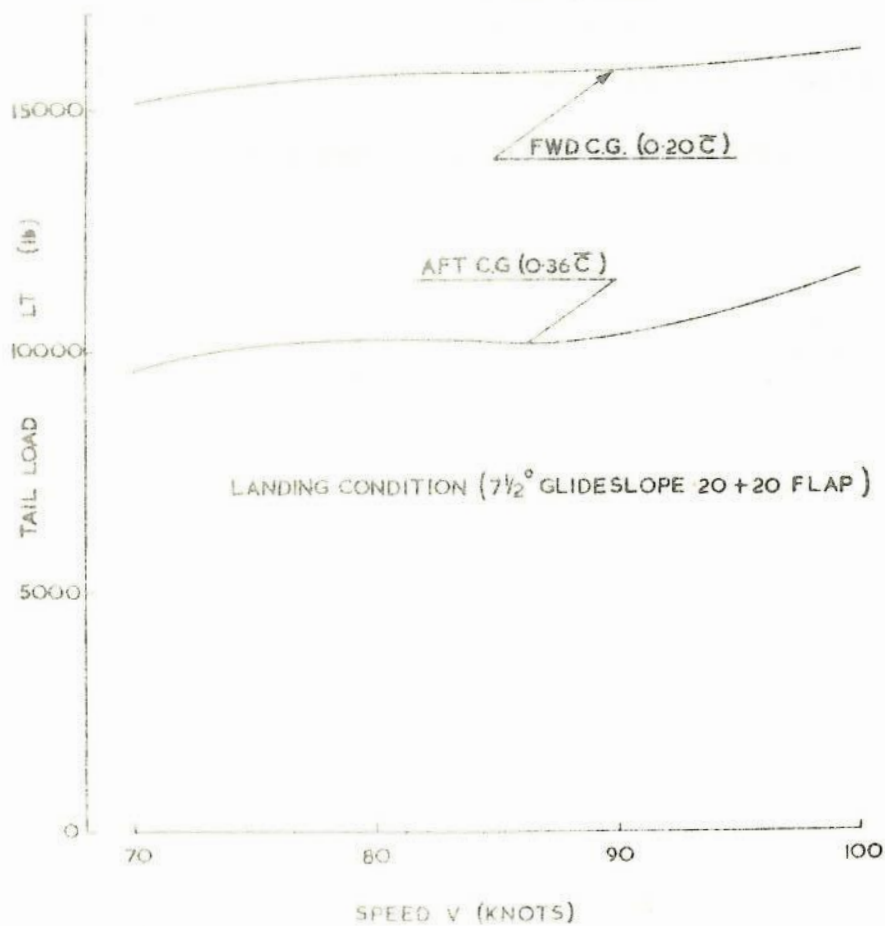
FIG 6.

VARIATION OF POWER SETTING WITH C_{μ} & SPEED FOR A71

LANDING CONDITION, ($7\frac{1}{2}^{\circ}$ GLIDE ANGLE $20 + 20$ FLAP)



DOWN TAIL LOAD FOR TRIM ON APPROACH



ELEVATOR REQUIRED FOR TRIM ON THE LANDING

APPROACH

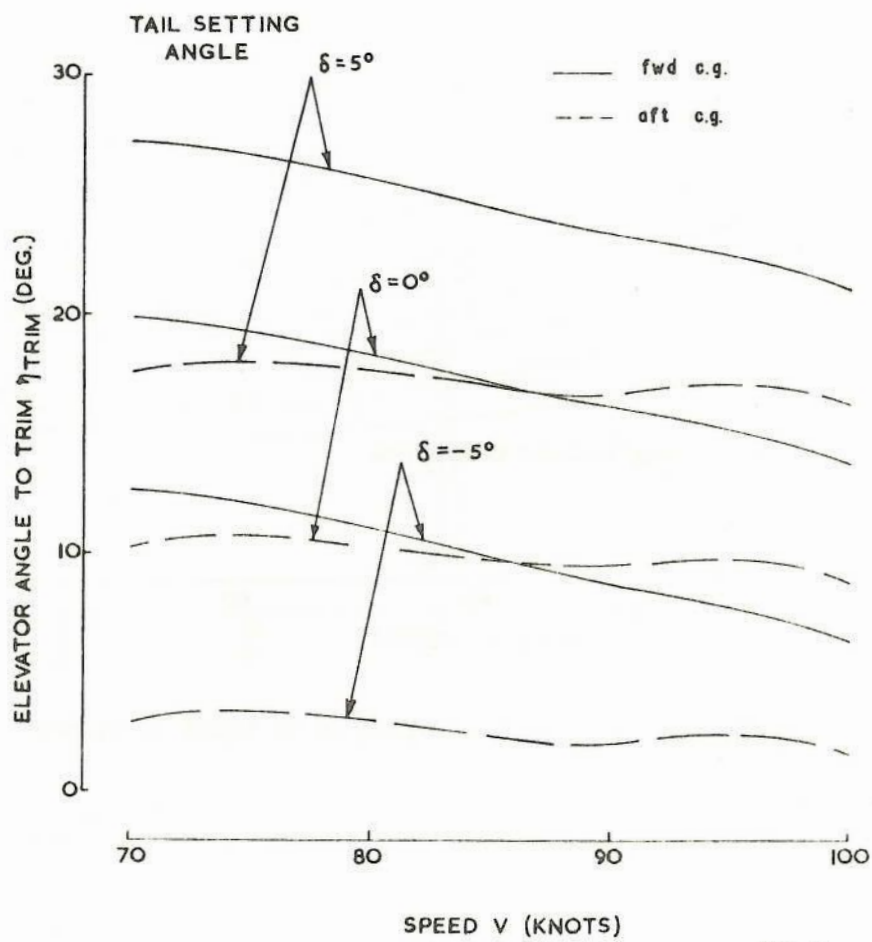
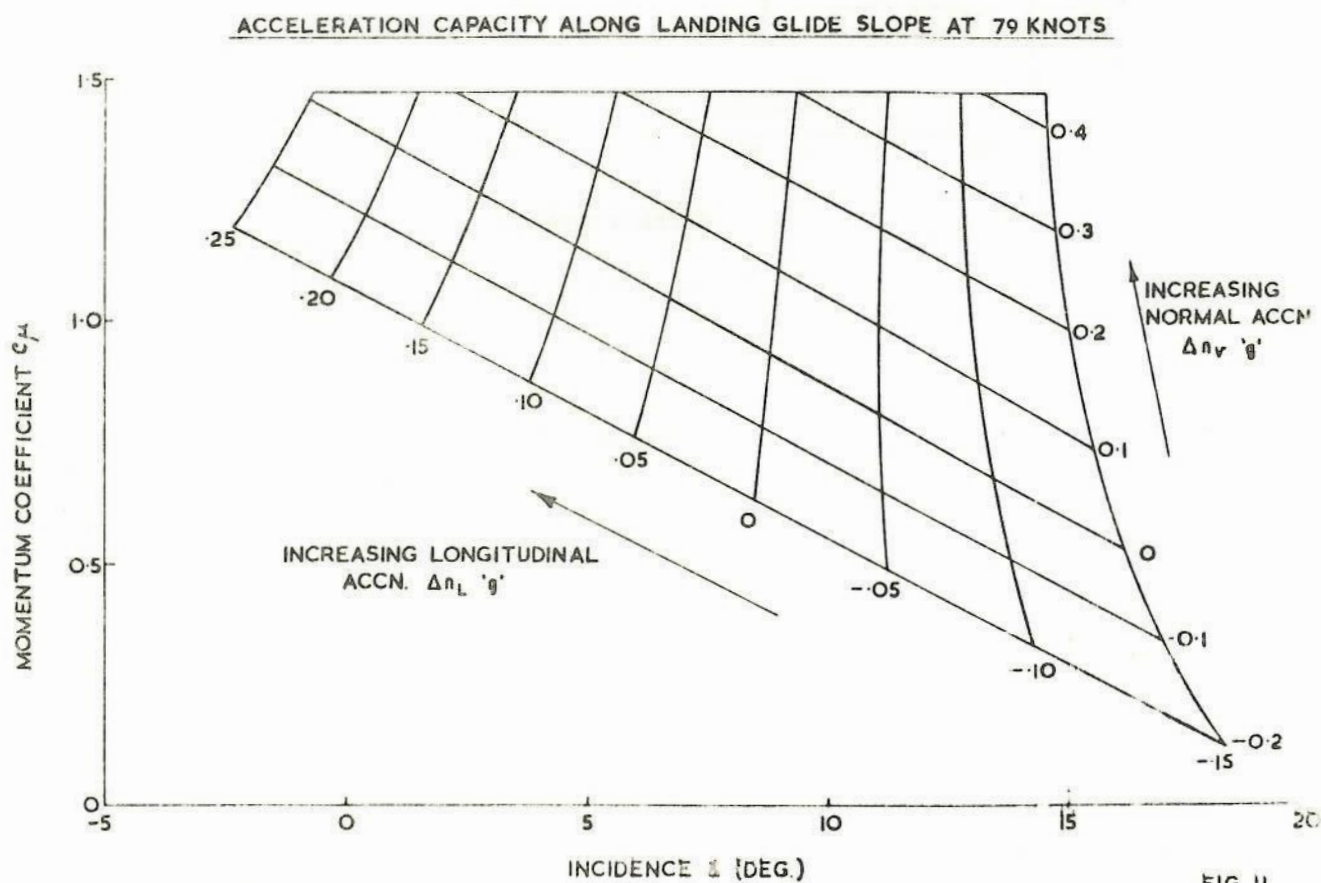
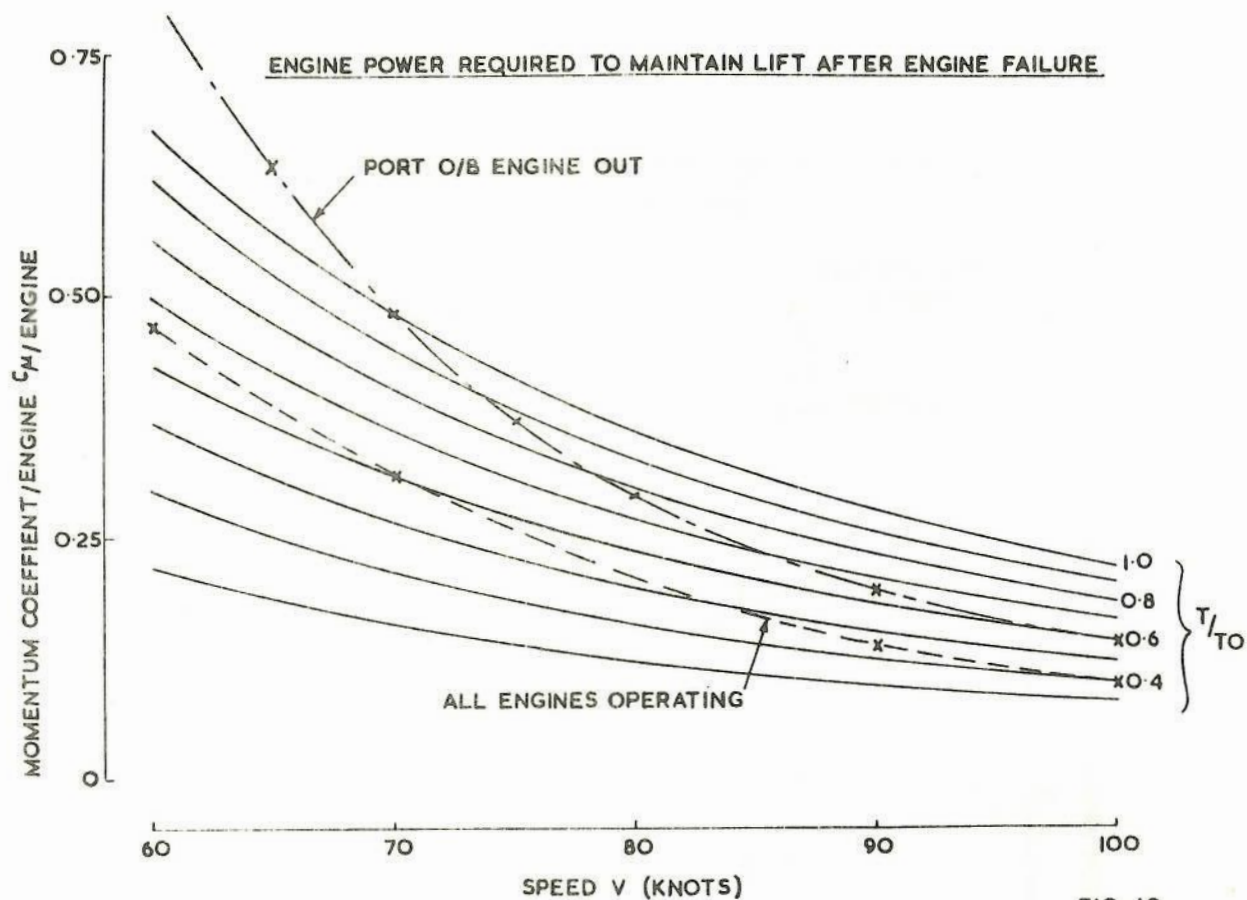


FIG 9.



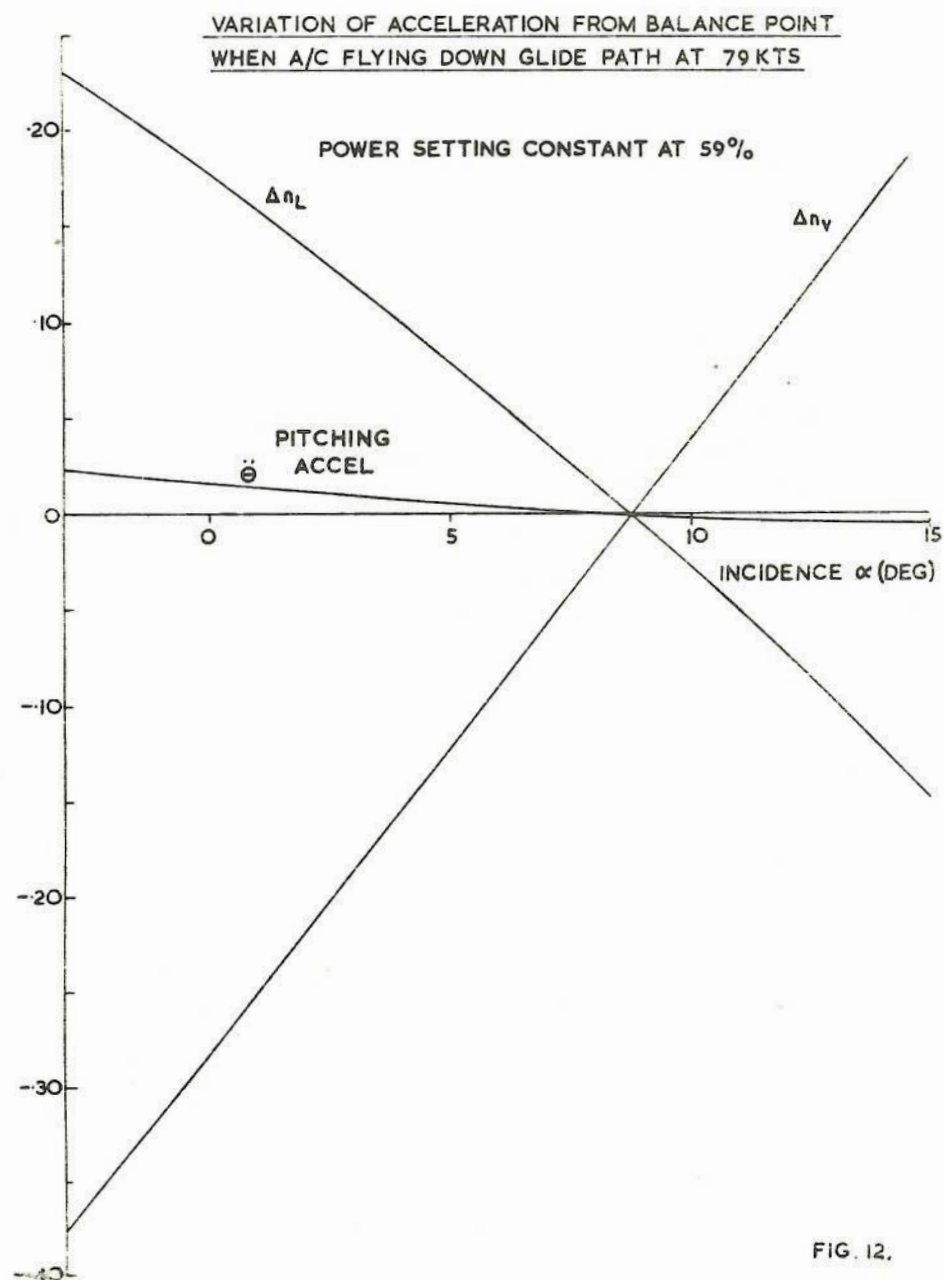


FIG. 12.

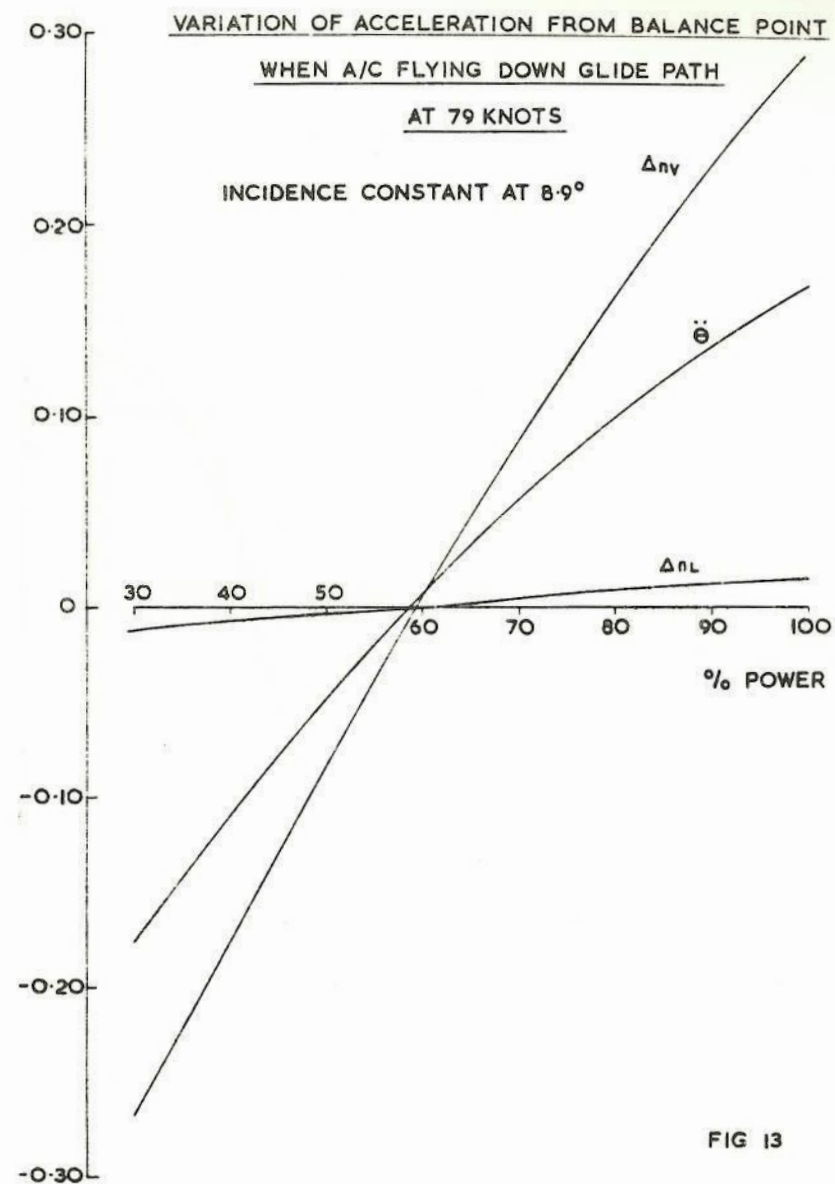


FIG 13

ELEVATOR REQD TO TRIM INCREASING POWER

AT 79 KNOTS

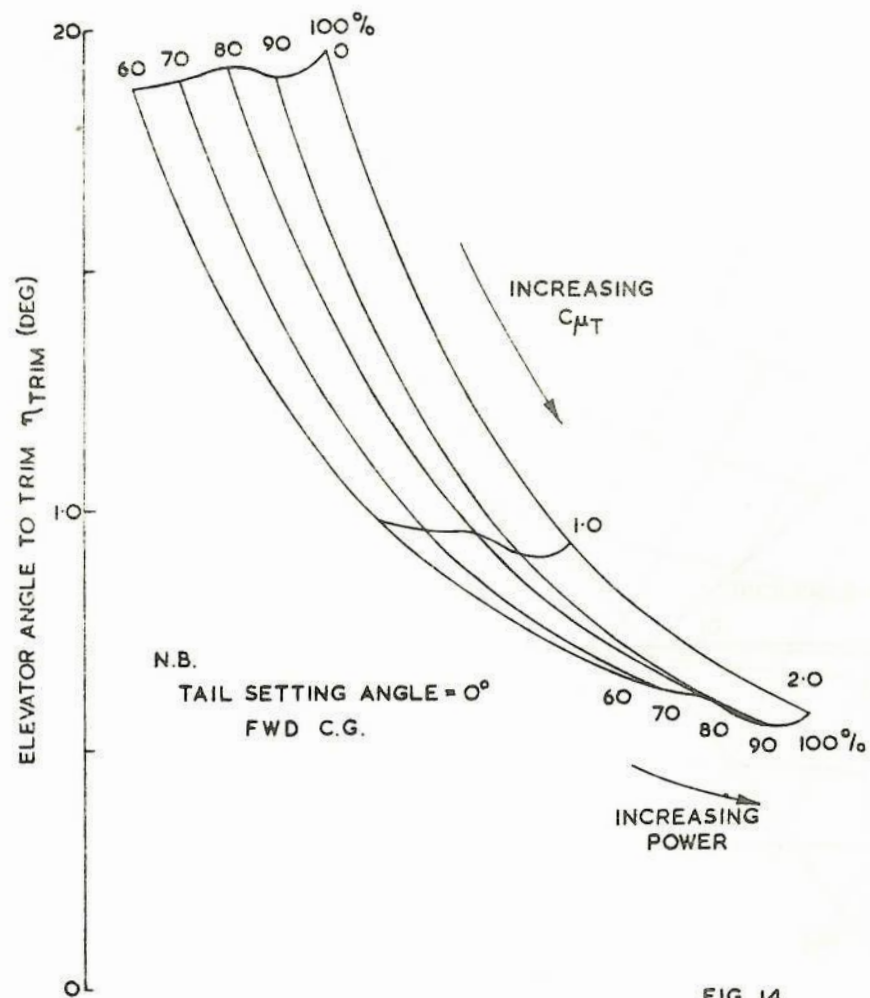


FIG 14

AIRCRAFT RESPONSE TO STEP ELEVATOR

AT 79 KNOTS APPROACH SPEED - $C_{\mu a} = 1.0$

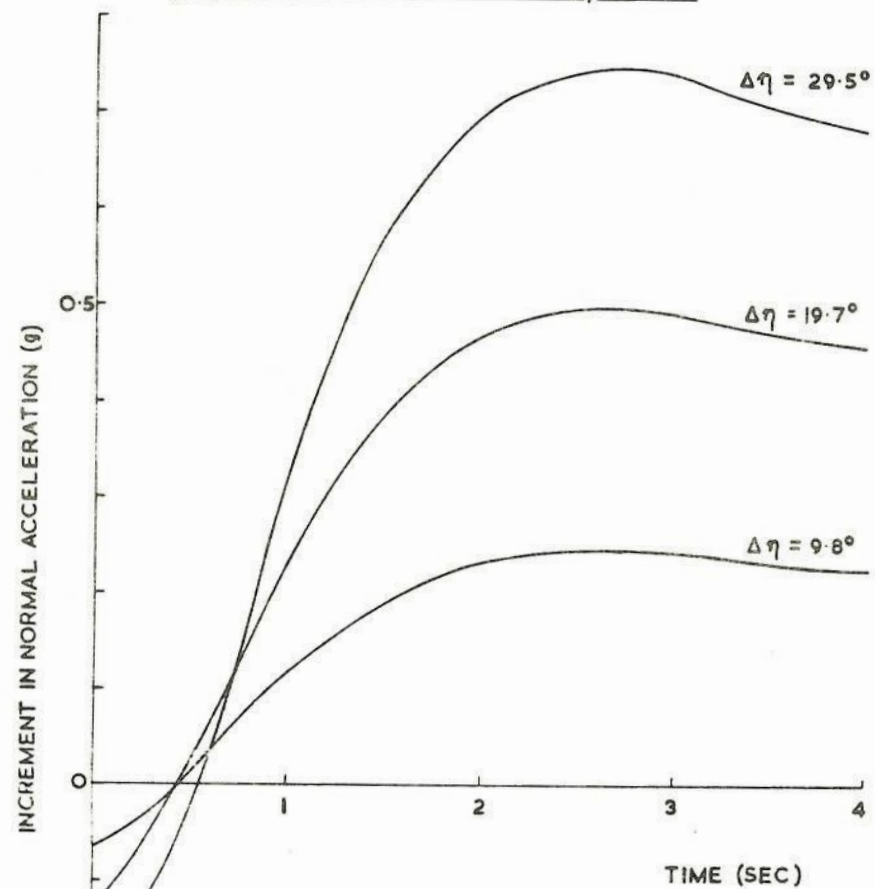


FIG 15

LATERAL STABILITY CHARACTERISTICS STICK FIXED ON APPROACH

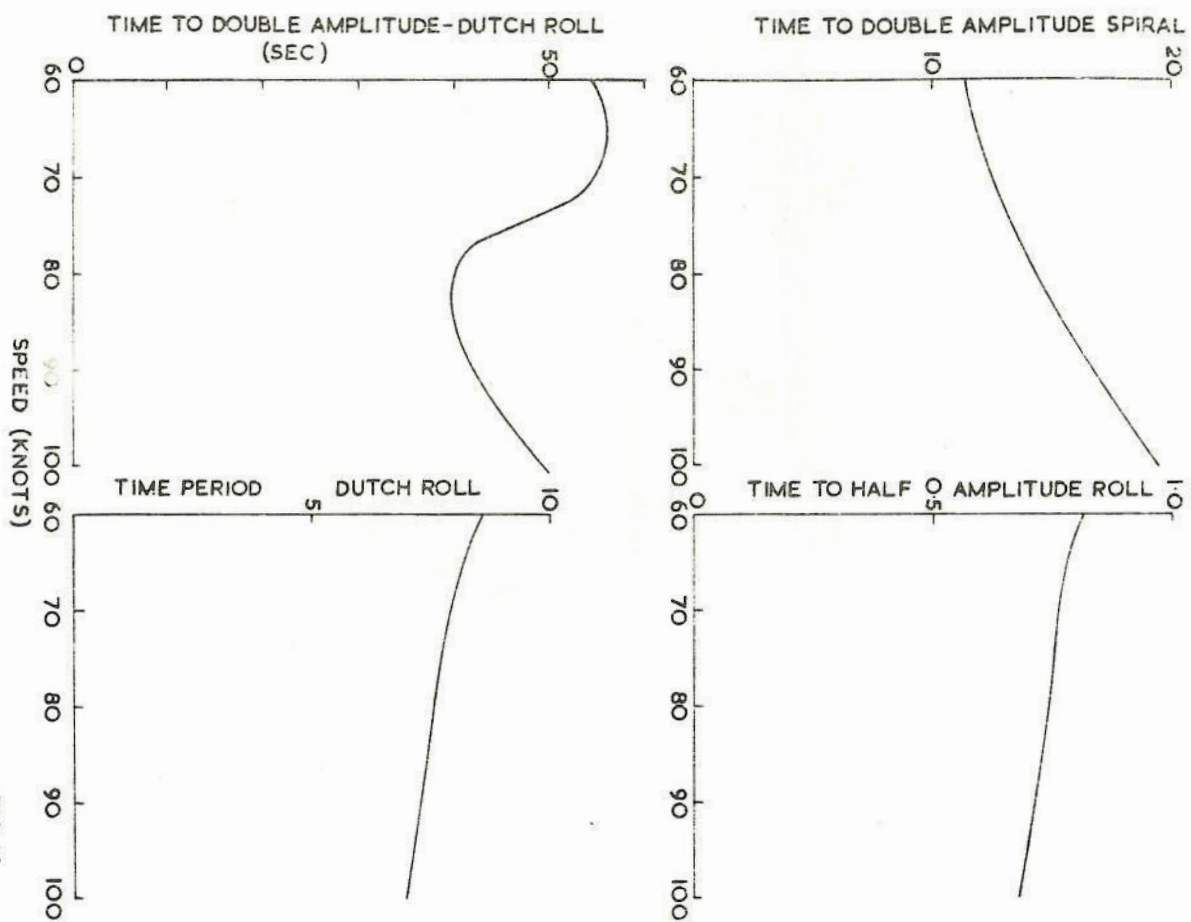


FIG 16

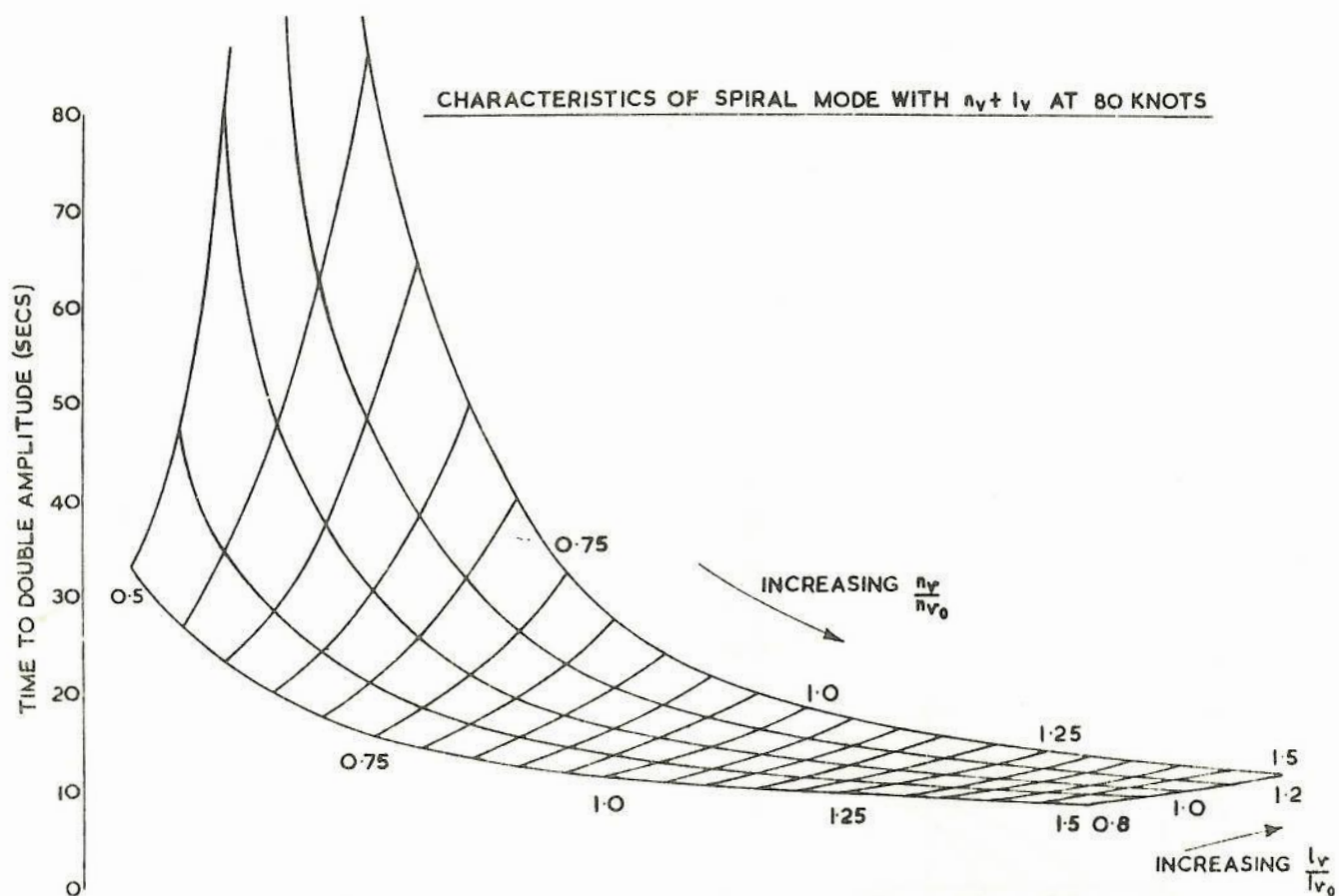


FIG 17.

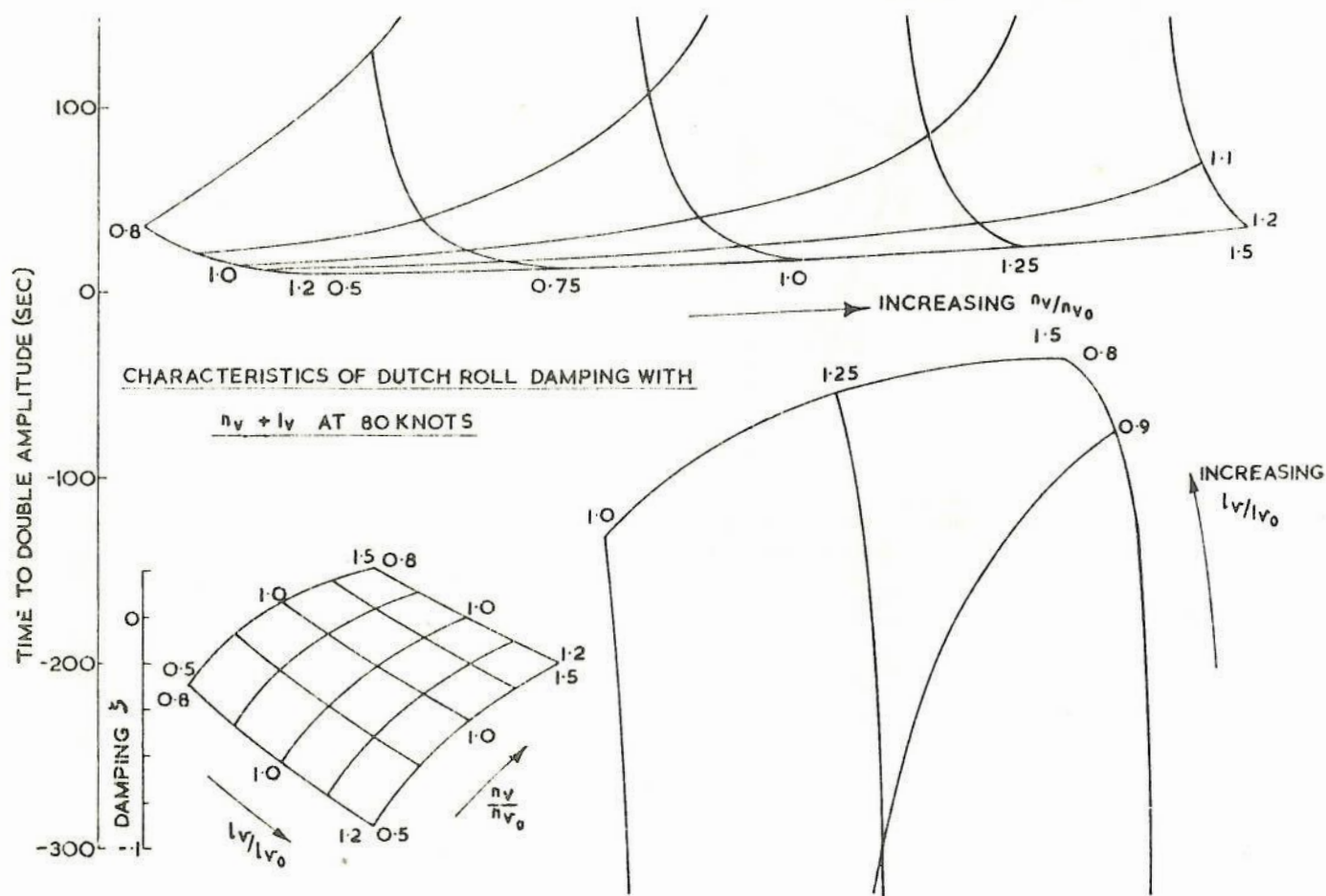


FIG 18

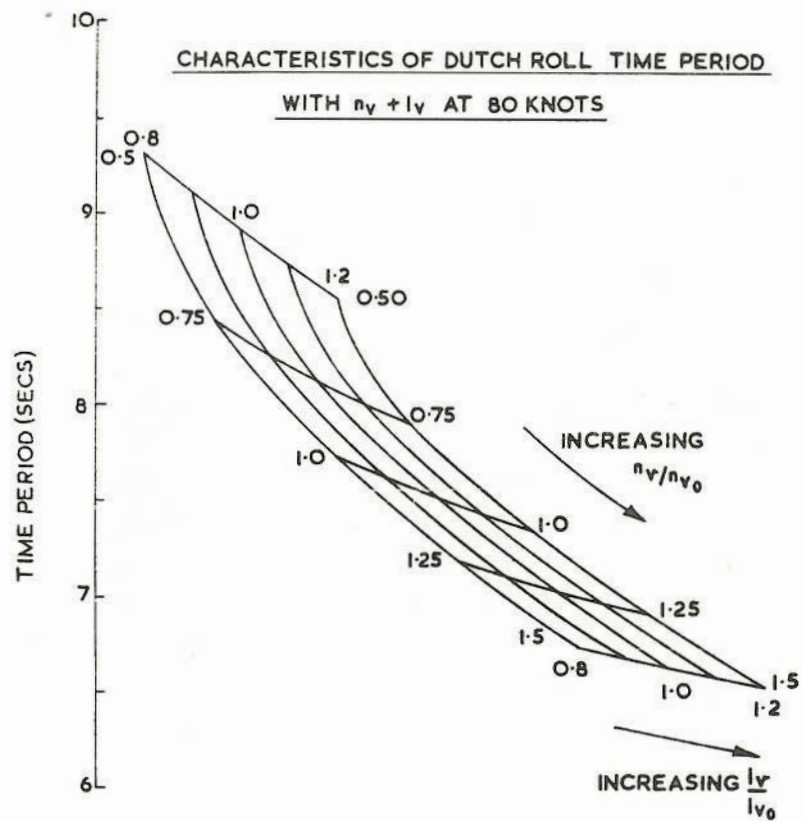


FIG 19

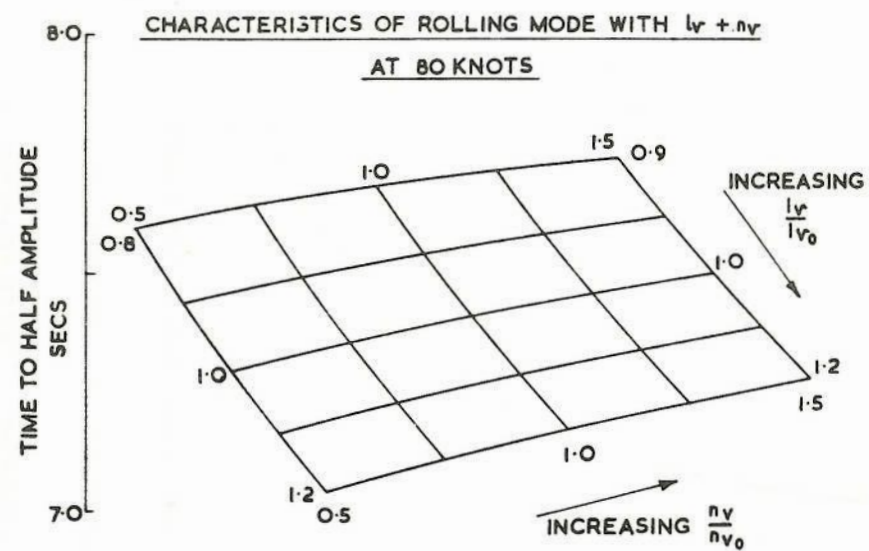


FIG 20

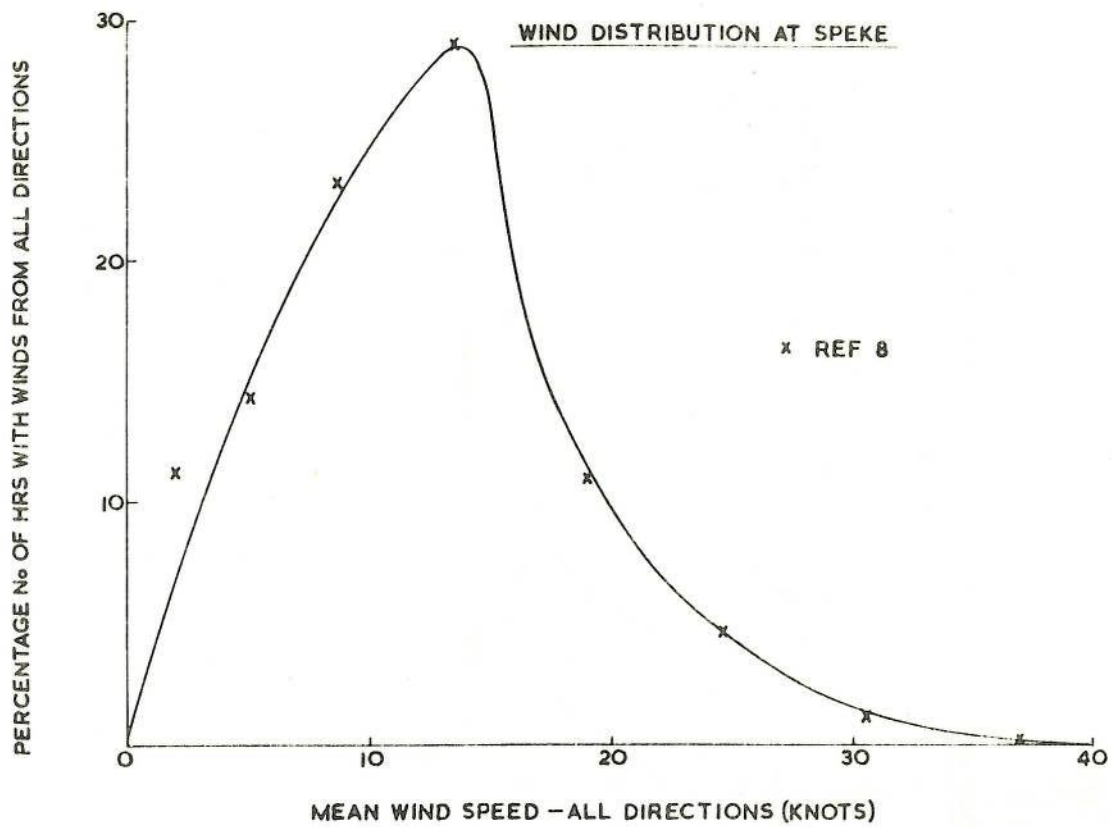


FIG 21

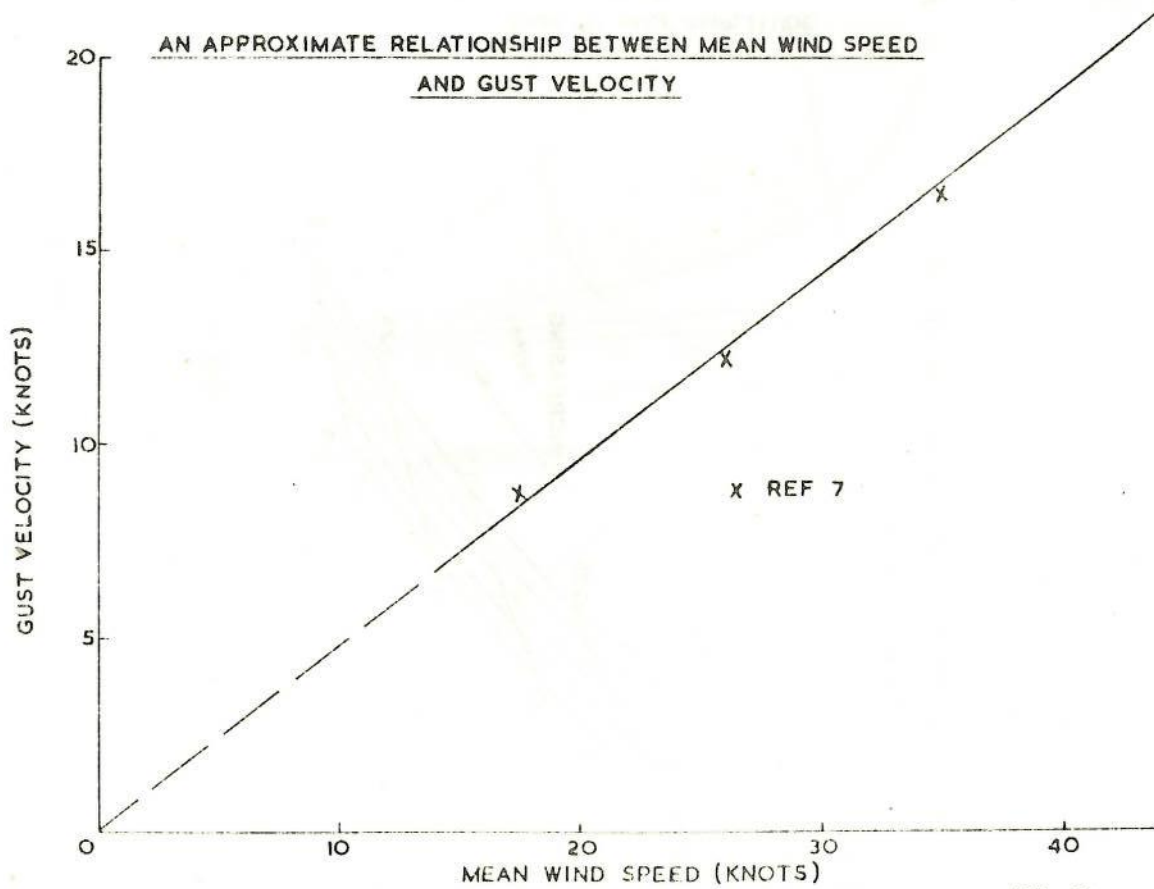


FIG 22.

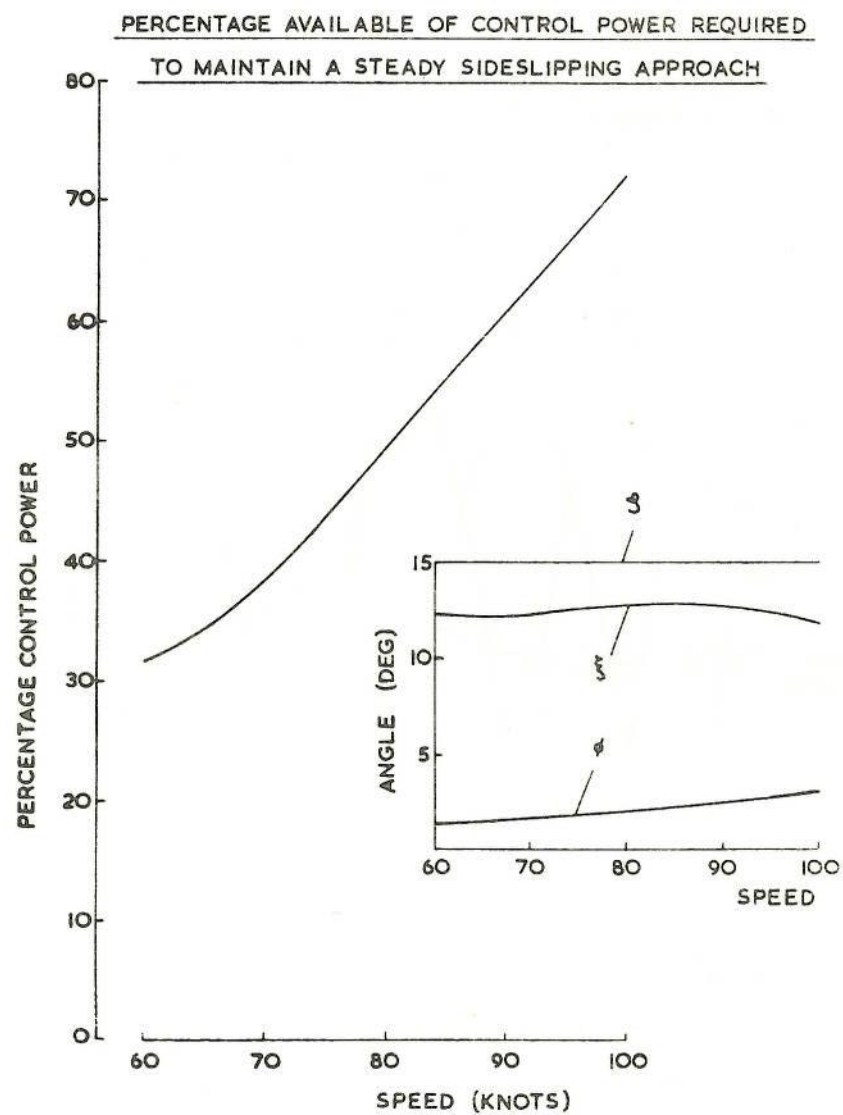


FIG 23.

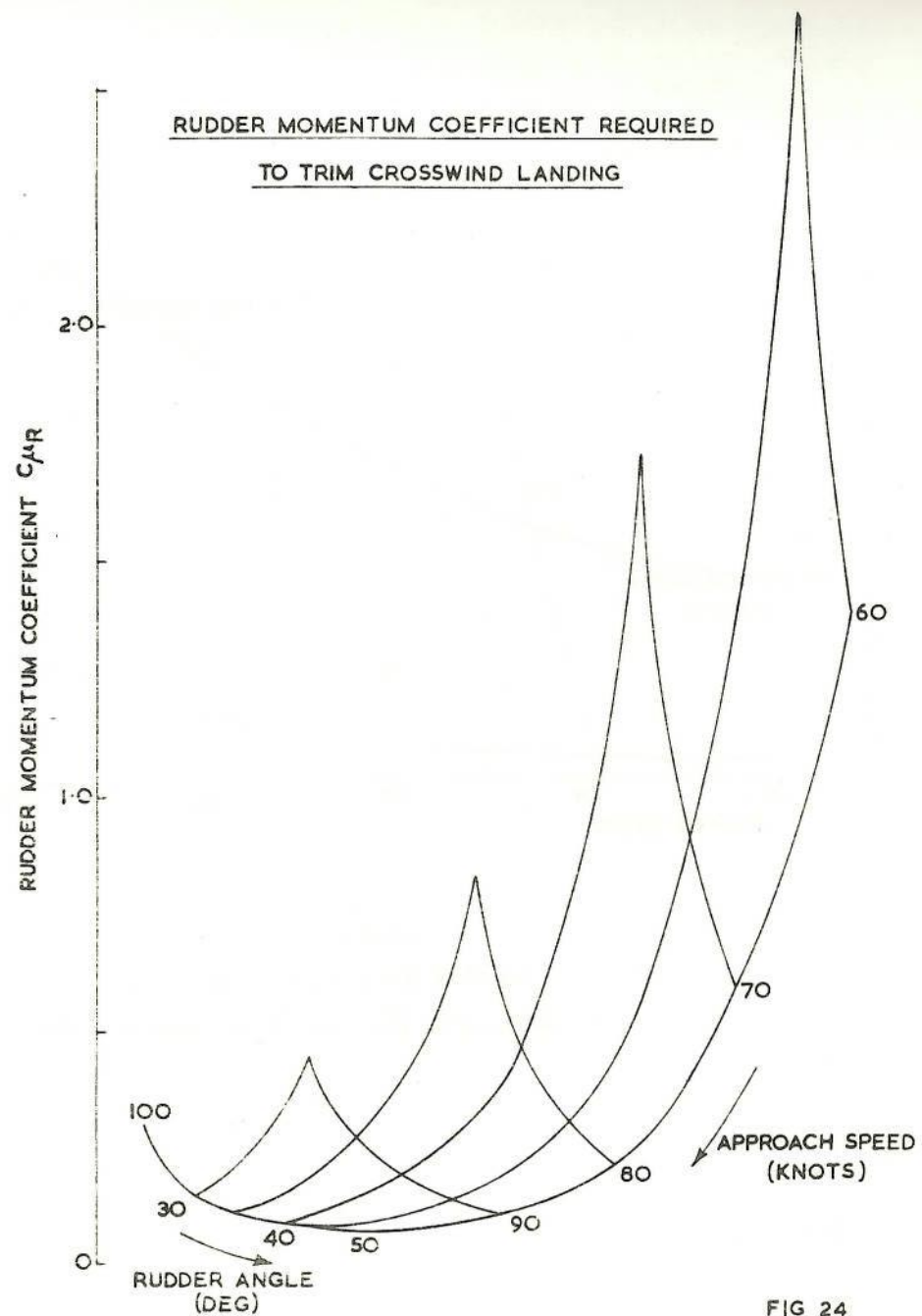


FIG 24

APU THRUST REQUIRED FOR RUDDER BLOW

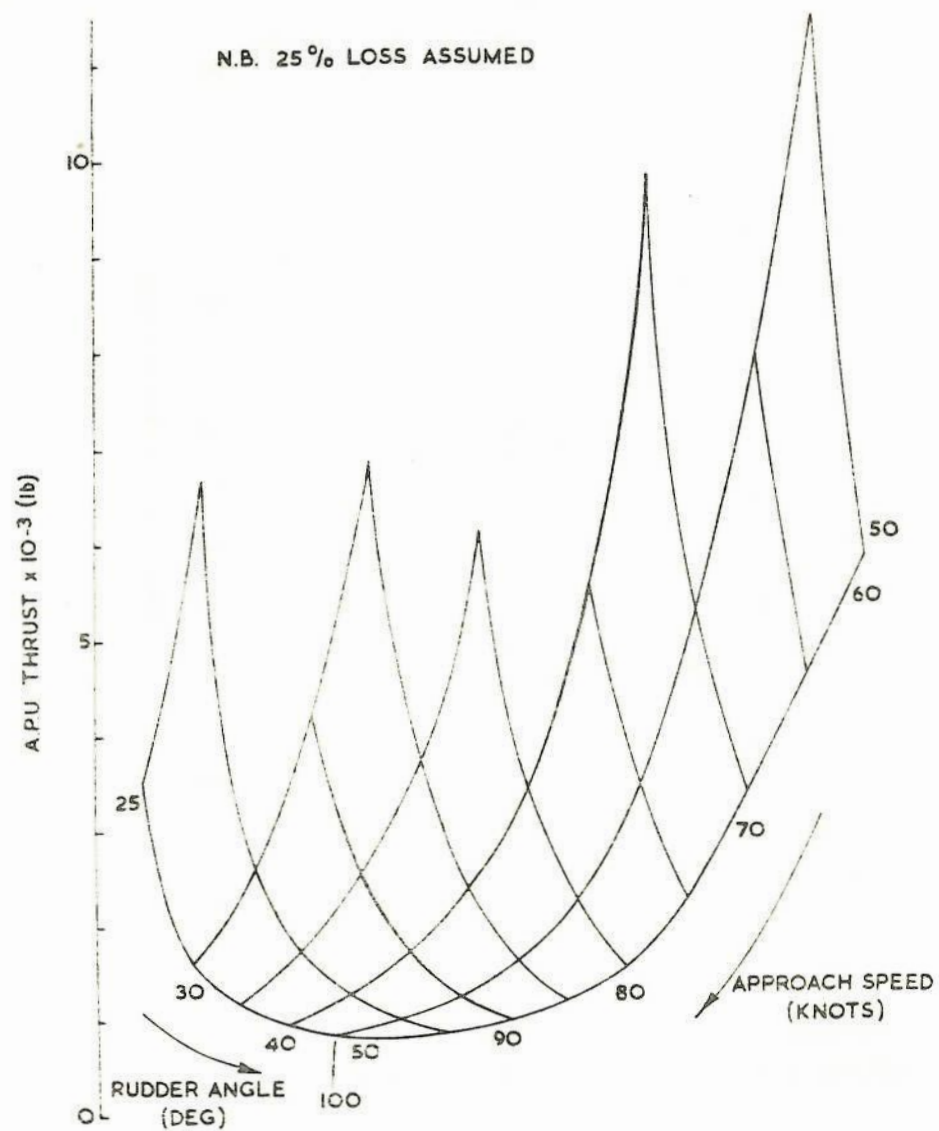


FIG 25

ROLLING AND YAWING MOMENT COEFFICIENTS DUE TO PORT O/B ENGINE FAILURE ON APPROACH

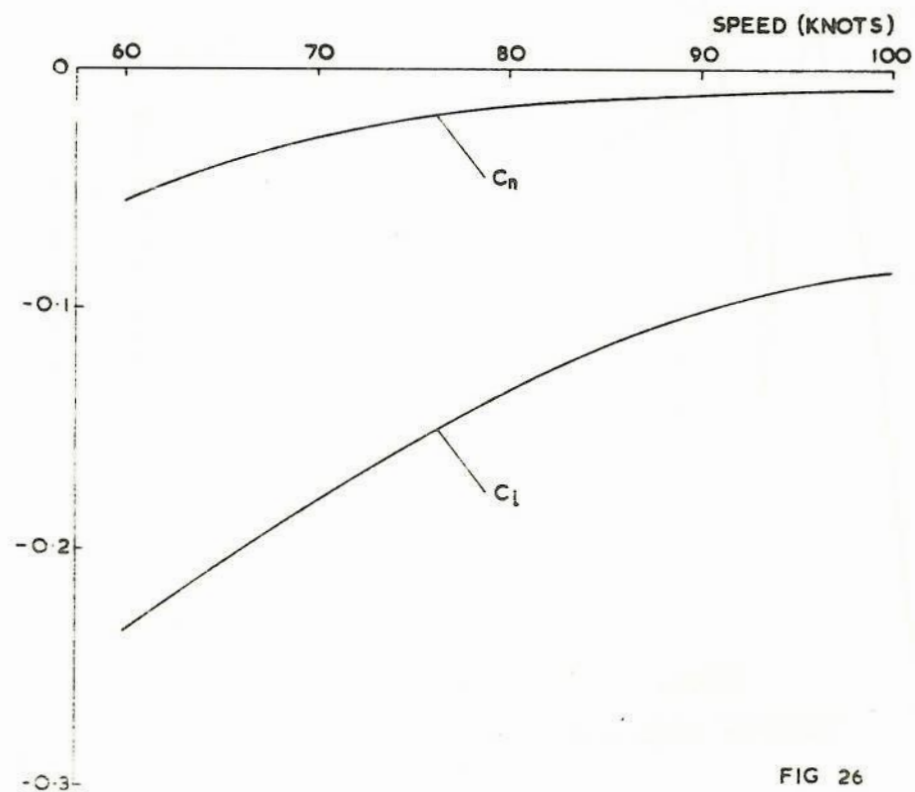


FIG 26

PERCENTAGE AVAILABLE OF CONTROL POWER REQUIRED
TO TRIM PORT O/B ENGINE OUT WITH ZERO SIDESLIP

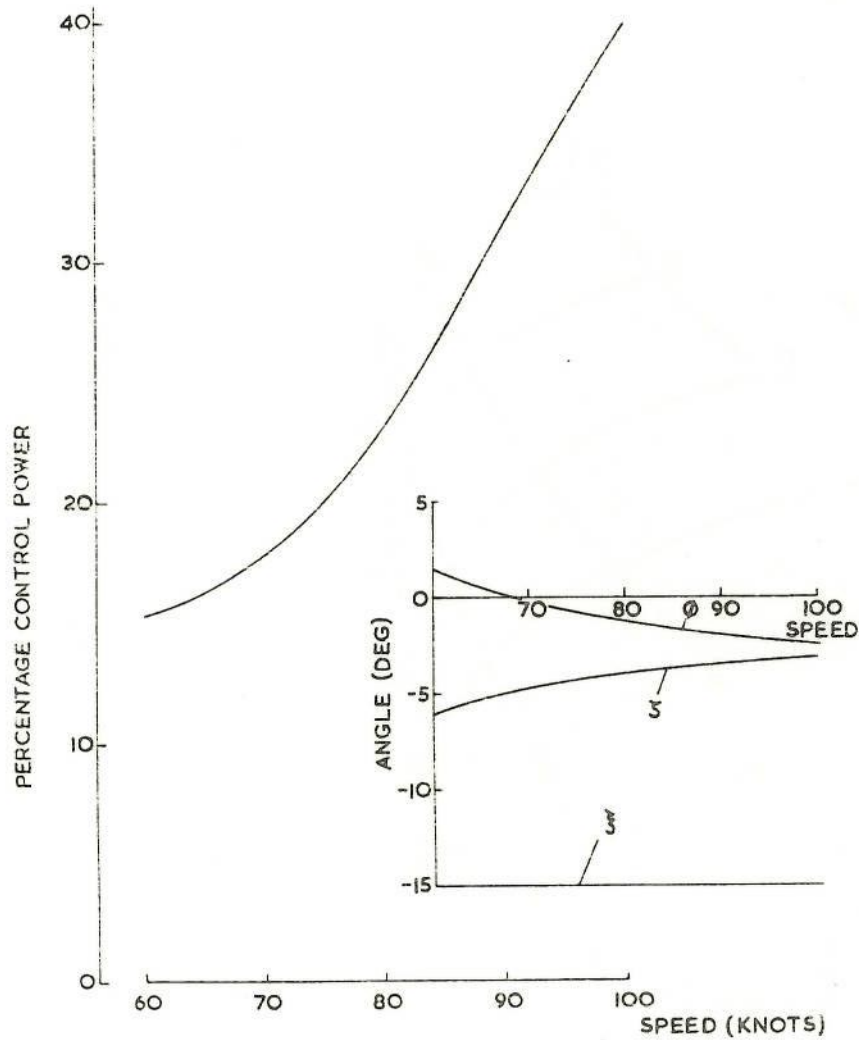


FIG 27

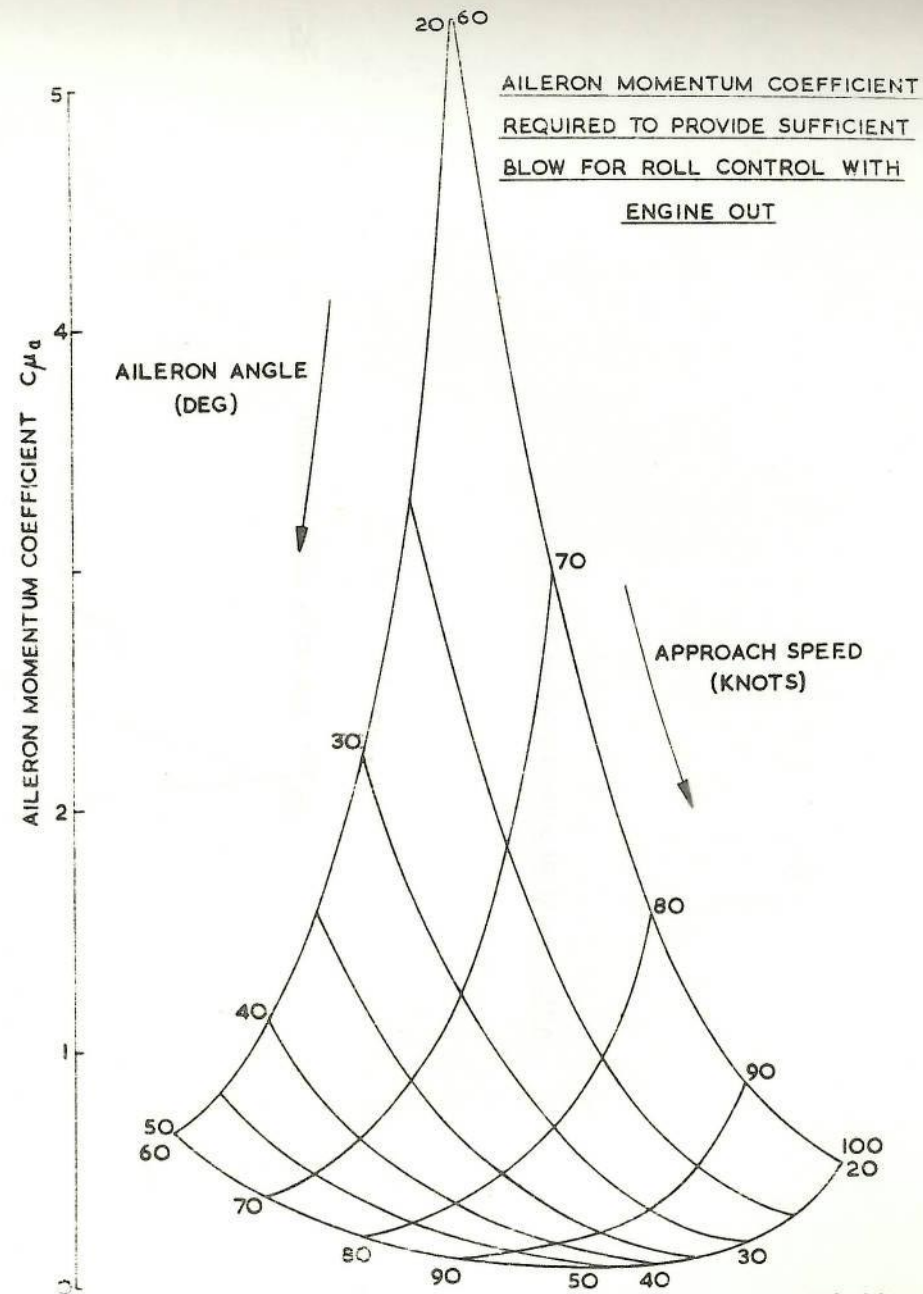


FIG 28

APU THRUST REQUIRED FOR AILERON BLOW

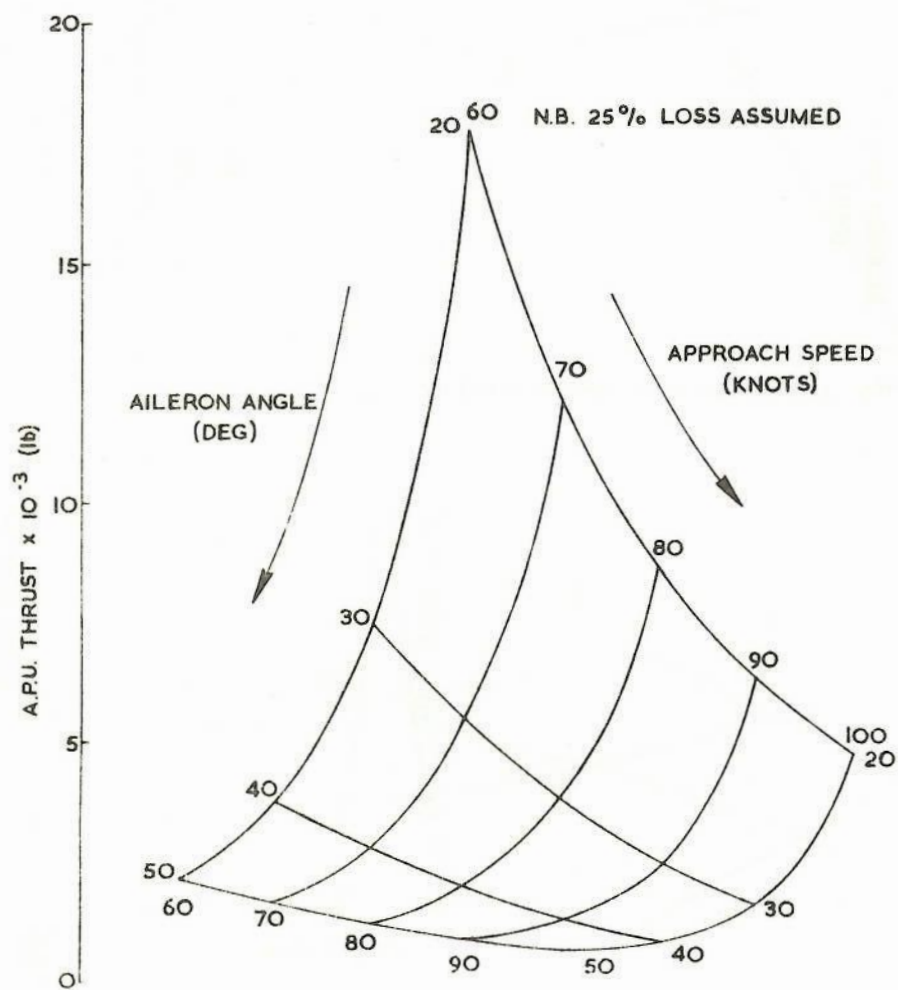


FIG 29